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Bridging analytical approaches for low carbon transitions[1]

Abstract:

Low-carbon transitions are long-term multi-faceted processes. While integrated assessment models (IAMs) have many strengths for analysing such transitions, their mathematical representation requires a simplification of the causes, dynamics and scope of such societal transformations. We suggest that IAM-based analysis should be complemented with insights from socio-technical transition analysis and practice-based action research. We discuss the underlying assumptions, strengths and weaknesses of three analytical approaches. We argue that full integration of these approaches is not feasible, because of foundational differences in philosophies of science and ontological assumptions. Instead, we suggest that bridging, based on sequential and interactive articulation of different approaches, may generate a more comprehensive and useful chain of assessments to support policy formation and action. We also show how these approaches address knowledge needs of different policymakers (international, national, local), relate to different dimensions of policy processes, and speak to different policy-relevant criteria such as cost-effectiveness, socio-political feasibility, social acceptance and legitimacy, and flexibility. A more differentiated set of analytical approaches thus enables a more differentiated approach to climate policy-making.

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Introduction

The climate change debate is shifting from problems towards potential solutions such as low-carbon transitions in buildings, energy, food and transport systems[1,2]. Clearly, several disciplines have studied such system transformations and can offer policy-relevant insights on how to promote such transitions, using different analytical approaches. One commonly used approach are quantitative models, including economic models and integrated assessment models (IAMs)[3,4]. IAMs describe both the drivers of environmental change (human systems) and the consequences of these changes (to environmental systems and their impacts). IAMs have many analytical strengths, such as their ability to combine scientific, engineering and economic information, their orientation to the future, their broad scope (which includes population dynamics, economic growth, and interactions between sectors), their capacity to make projections at an aggregate global level, and their ability to simulate different mitigation pathways and policy scenarios[5]. Other social science approaches, however, also provide key insights into transitions, for instance with regard to the actors involved, their interactions, and the development and implementation of different kinds of innovation. In the paper, we will argue that a comprehensive analysis of low-carbon transitions should draw on IAMs as well as other social sciences[6-13].

There is an ongoing debate about the relations between IAMs and other social sciences. One view is that social science concepts and theories should be integrated within quantitative models. Earth System models, for instance, convey the ambition of a holistic super-discipline that aims to understand the whole planet as an integrated whole with coupled human and ecological systems[14,15]. We believe this approach faces epistemic problems because of fundamental differences between approaches. Another view is that IAMs and social sciences are incommensurable and should be applied separately in a pluralist way[16]. For instance, Castree et al. argued against the notion of a 'single, seamless concept of integrated knowledge'[17]. In response to comments, Castree subsequently suggested that "the challenge is deeper and wider" with regard to knowledge integration than commentators have acknowledged[18].

We aim to contribute to this debate by further addressing some of the foundational assumptions that complicate integration between IAMs and the wider social sciences. These assumptions relate to philosophies of science and ontologies of social action. We aim to make these abstract ideas more concrete by distinguishing three approaches for the analysis of the role of innovation in low-carbon transition pathways: 1) IAMs, which offer aggregate goal-oriented techno-economic analysis of different mitigation pathways, 2) socio-technical transition analysis, which offers meso-level assessments of social groups in relation to radical change in socio-technical systems, 3) practice-based action research, which take an action-orientation to local initiatives, engaging in the co-production of on-the-ground change processes with social actors. We will discuss the assumptions, strengths and weaknesses of these approaches, and address policy implications.

The paper's argument is developed in five subsequent sections. First, we articulate the main characteristics of low-carbon transitions, using examples from the energy domain. Secondly, the paper identifies why transitions pose some analytical challenges for IAMs, and what responses have been developed to address these. The third section broadens the scope beyond IAMs by addressing foundational issues in the social sciences and their implications. While IAMs represent a positivist philosophy of science, this discussion shows that there are alternative scientific styles such as post-positivism (critical realism), constructivism, and relativism (postmodernism), based on different assumptions and methods. This discussion also shows that rational choice, which informs IAMs, is only one social science ontology. There are other ontologies such as interpretivism, structuralism and conflict theories, which highlight different dimensions of social realities and low-carbon transitions. The fourth section discusses three approaches for the analysis of low-carbon transitions, which are based on different philosophies of science and ontological assumptions. These approaches are: IAMs, socio-technical transition theory, and practice-based action research. The fifth section addresses bridging and governance implications in relation to these approaches.

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Characteristics of low-carbon transitions

Low-carbon transitions refer to major changes in buildings, energy, and transport systems that substantially enhance energy efficiency, reduce demand or entail a shift from fossil fuels to renewable inputs. These system transitions entail not only technical changes, but also changes in consumer behaviour, markets, institutions, infrastructure, business models and cultural discourses[19]. The various dimensions interact and co-evolve with each other as the UK Committee on Climate Change notes: "The roll-out of low-carbon technologies (like electric and plug-in hybrid vehicles, heat pumps, district heating, smart meters, solid wall insulation) will be, in part, driven by changes in behaviour (e.g. consumers demanding new goods and services) and will also itself change behaviour (as consumers and businesses use the technologies)"[20].

Transitions and system innovation are enacted by a wide range of actors such as firms, consumers, national policymakers, local authorities, researchers, social movements, wider publics[21,22]. These actors often have different interests, resources, capabilities, and different beliefs about preferred low-carbon solutions. Transitions therefore commonly involve struggles, including *business struggles* between incumbents and new entrants[23] (which involve industry structures, market power, alliances, and strategies), *discursive struggles* in public debates[24] (which involve claims and counterclaims, framing contests, and arguments over credibility and legitimacy) and *political struggles* over goals, policy frameworks and the setting of specific instruments[25,26]. Because of the unpredictability of these struggles, system innovations are characterized by emergent and non-linear dynamics[27,28] . Text box 1 provides some examples of the non-linear effects of social (inter)actions and struggles on low-carbon innovation.

TEXT BOX 1 ABOUT HERE

Historians of technology further emphasize that historical energy transitions were associated with wider socio-economic transformations. David Nye, for instance, concludes that historical energy transitions "were not merely substitutions of one energy source for another but reorganizations of society, including transportation systems, population distribution, and the organization of work"[29]. Hirsch and Jones further suggest that historians can contribute to energy research by drawing attention to "social and political impediments that designers of new technologies frequently cannot imagine" and to "the social context in which people create, deploy, and use technologies"[30]. These historical insights suggest that future energy transitions are likely to also involve broad transformations. Miller, Iles and Jones, for example, suggest that "efforts to transform energy systems involve changes, therefore, not only to energy technologies and prices but also to the broader social and economic assemblages that are built around energy production and consumption"[21].

These kinds of processes, and the social, political and cultural reconfigurations they entail, are difficult to incorporate in models as simple, general mathematical equations. The analytical challenge of low-carbon transitions is increasingly recognized. Nicholas Stern[31], for instance, says that he would "place still more emphasis on a Schumpeterian interpretation of learning, rapid technological change, and radical change in structure." Michael Grubb and colleagues also conclude that "to solve problems that span so many dimensions of human systems, we need to draw on multiple theories"[32]. Specifically, they suggest that neo-classical economics should be complemented with insights from behavioural economics (to include more realism into short-term decision making) and evolutionary economics (to better address innovation and long-term system transformation). The latter would, amongst others, draw attention to 'creative destruction' and potential losers in low-carbon transitions, such as fossil fuel producers[33].

Analytical challenges for integrated assessment models

While integrated assessment models (IAMs) represent formidable analytical strengths for the exploration of low-carbon transitions, their mathematical representation requires some simplification. This implies that models may have limitations because of their aggregate orientation, their focus on technological mitigation pathways, their reliance on specific simplifications based on economic theories, and their assumptions about governance[4,34,35]. We briefly elaborate these points, not to discredit IAMs, but to underpin the need for complementary analytical approaches.

- Low-carbon transitions and innovation efforts unfold at multiple scales. IAMs typically focus on specific scale(s), often the global scale, which means that lower scales receive less attention. The interaction between different scales is important, however, because this is where contextual interactions between policymakers, firms, civil society groups, media and consumers shape the development and deployment of low-carbon options in specific energy, housing and transport systems. While IAMs can play interesting roles in connecting various scales, especially the global scale to the national/regional scale and the total economy to specific sectors, they face difficulties in accommodating the groundswell of local initiatives (transition towns, community energy, urban innovations) aimed at reconfiguring local transport systems and buildings[36,37]. The reason is that the need to simplify the representation of complex systems complicates the inclusion of local heterogeneity.

- IAMs typically conceptualize systems as collections of technologies and their interactions, and understand transitions as changes in consumption and production patterns, technologies and resources[4]. This means that many IAMs neglect the role of organisational, social and business model innovations in low-carbon transitions. Most IAMs also pay limited attention to the co-evolution of energy technologies and wider contexts, which historians highlight[29,30]. IAMs also tend to downplay qualitative changes in transitions that alter the way systems are structured and function, as Bai et al. suggest: "the parameters for judging the performance of systems themselves will change. Systems may also change their structure, i.e. their functional architecture of parameters"[38].
- To simplify, many IAMs rely on mainstream economic theories, which make restrictive assumptions about the behaviour of social actors, e.g. actors have complete information, perfect foresight, rational decision-making, competitive price-taking behaviour (no monopolies or strategic behaviour)[39]. Because of these assumptions, price developments (which may be affected by policies and endogenous technical change) are the main drivers of IAM-based mitigation pathways. While prices and cost-benefit calculations are certainly important in low-carbon transitions, other behavioural factors also shape actions by firms,

consumers, and policymakers, e.g. routines and capabilities[40], norms and conventions[41], belief systems and interpretations[42]. Struggle, conflict, negotiation and strategic behaviour are also important in transitions, including resistance to change from powerful social and business interests[39,43]. These social and political processes are difficult to accommodate in IAMs, even as they have material impacts on transitions to low-carbon energy systems.

- With regard to governance, many IAMs assume a "fully informed benevolent social planner"[39] that can shape the system from outside (although some recent studies also include decision-rules that lead to less optimality). Given their economic assumptions, IAMs commonly recommend price-oriented mitigation policies (via taxes or emission trading), with some studies also including investments in R&D or learning-by-doing[44]. This approach to governance downplays three issues. First, policymakers (particularly at national and local levels) are usually constrained by their dependence on other actors (e.g. firms, electorates, civil society) for skills, financial resources, deployment and legitimacy[45]. Because of these dependencies, studies should "make the social and political *contextual factors* with respect to the choice and implementation of a technology path more explicit" (italics in original)[46]. Second, since IAMs privilege price-based instruments, they restrict consideration of a wider range of policy instruments[44]. While carbon price instruments could, in principle, be effective, the International Energy Agency notes that: "More successful forms of intervention, so far, have included capital grants, tax breaks, production subsidies and performance standards"[47]. Third, whereas IAMs assume that policymakers are mostly motivated by cost considerations and climate change problems, real-world policymakers in energy, transport, and agro-food systems seek to reconcile climate objectives with a range of other normative goals and objectives, e.g. congestion, safety, health, jobs, competitiveness.

Modellers have developed various responses to address these problems. One response is to ask stakeholders to evaluate the plausibility and social acceptance of model outcomes and low-carbon scenarios[48]. This response introduces more social realism and other considerations besides costs, but relies on the opinions of specific groups of stakeholders, rather than social scientists, for the analysis. A second response is to use historical data of past transitions to assess future transitions produced by IAMs and energy-economic models[49]. This response also introduces more realism, but may face difficulties in addressing specificities that make low-carbon transitions different from historical transitions (e.g. climate change as a collective good problem, low-carbon innovations failing to meet consumer preferences)[50]. A third response is the development of models with different assumptions and structures that accommodate techno-economic detail, actor heterogeneity and transition pathway dynamics[51,52]. This response remains within the modelling paradigm, but introduces more realism with regard to agency and also allows for social innovations (e.g. changes in consumer behaviour). A fourth response is to interpret mitigation pathways from IAMs as 'first-best world' possibilities, based on idealized economic assumptions[32]. Real-world studies of low-carbon innovation would then investigate 'second-best worlds' that include more differentiated kinds of behaviour and political economy obstacles[39]. A problem for this response is that real-world developments may go faster than model projections. For example, the diffusion of solar-PV, onshore wind turbines, and LED-lighting has been faster in recent years than was anticipated in earlier model studies[53]. Ackerman and colleagues more generally suggest that "IAMs typically adopt conservative assumptions about the pace of technical change" and may "overestimate the costs of achieving stabilization targets"[54]. A fifth response is to integrate the social sciences into models, as proposed in the context of Earth System models[14,15]. This response encounters problems, however, because the

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Wilson, C., Grubler, A., Bauer, N., Krey, V. & Riahi, K. Future capacity growth of energy technologies: Are scenarios consistent with historical evidence? *Climatic Change* **118**, 381-395 (2013).

social sciences are characterized by several foundational differences, which get in the way of full integration, as the next section explains.

In sum, the modelling community has developed several innovative responses to address challenges associated with low-carbon transitions. But it also shows that each response has limitations. We therefore agree with Castree that the challenges are 'deeper and wider' and warrant further reflection on foundational assumptions in the social sciences and the difficulties these pose for integration[18].

Foundational differences and difficulties for integration

Most pleas to integrate the social sciences in climate change research[6,7,55] portray different social sciences as addressing different *topic areas*. Psychology, for instance, is portrayed as dealing with individual attitudes and decisions; management and business studies as dealing with firms; sociology as dealing with society and social groups; cultural studies and anthropology as dealing with culture; political science as dealing with power and policy-making. Such representations are convenient, because they suggest that different social sciences represent parts of the "research puzzle"[6] that can be fitted together since they represent different domains or aggregation levels (individual, group, firm, society). The problem with such representations is that they ignore foundational differences within the social sciences that complicate integration attempts. One foundational difference is the existence of different philosophies of science, based on different assumptions about reality, explanatory goals and methodologies (Table 1).

TABLE 1 ABOUT HERE.

A second important difference is the existence of different ontologies in the social sciences[56-58], which relate to basic assumptions about core characteristics of social entities (in this case, causal agents) and what causal mechanisms explain stability and change. Table 2 summarizes the main characteristics of four important social science ontologies, with the third column relating them to aspects of low-carbon transitions.

TABLE 2 ABOUT HERE.

Because of these fundamental differences it is difficult to integrate social science theories in a synthetic meta-theory which can, in turn, be folded into a comprehensive model of physical, technological and social reality. Instead, social sciences are characterized by different research styles and cultures of inquiry[59-61].

In the context of energy research and climate change, this means that an over-arching super-integration of social sciences in IAMs is unlikely[18]. Some social science theories, which adhere to a positivist philosophy of science and work within a rational choice paradigm (e.g. mainstream economics, operations research, some planning and management theories), may be integrated in IAMs because of shared assumptions and methods. But other social science theories with different ontologies (e.g. interpretivism, structuralism, conflict theories) and philosophies of science cannot feasibly be integrated into IAMs. These other theories do, however, address important dimensions of low-carbon transitions, including power, conflict, discourse, learning and norms. We therefore argue that the analysis of low-carbon transitions should be based on a *plurality* of approaches, with bridges enabling dialogue and interaction, rather than seamless integration.

Three approaches for analysing low-carbon innovation and transitions

With regard to the analysis of low-carbon innovation in transitions, we suggest that three approaches can fruitfully complement each other: IAMs, socio-technical transition theory, and practice-based action research. These three approaches respectively represent the first three philosophies of science in Table 1.

Integrated assessment models (IAMs) are useful because they: 1) enable future-oriented explorations of diffusion and costs of different low-carbon technologies, 2) accommodate interactions between various domains, 3) assess sustainability *outcomes* of different mitigation pathways in relation to future policy targets (e.g. a 1.5°C target for global climate policy), 4) generate proposals for policies needed to achieve specified targets[4,62]. Assumptions about innovations and policy can be varied in different model runs and scenarios. IAMs have made progress in modelling endogenous technical change, especially by including R&D-induced technical change and learning curves[63]. While these improvements enable quantitative modelling of long-term technological diffusion, Gillingham and colleagues also note that they "miss some important phenomena underlying the complex nature of technological change" and "struggle with an inherent lack of empirical data to calibrate model parameters"[63]. Policymakers are assumed to be external actors and able to affect transitions through policy instruments, with a stress on price-based instruments.

Socio-technical transition theory is useful because it offers a contextual analysis of innovations and actors in specific sectors and systems[64,65]. The multi-level perspective (MLP), in particular, offers a heuristic framework of how radical low-carbon innovations, which are conceptualized as emerging in niches[66], struggle against existing socio-technical regimes, which are characterized by path dependence and lock-in mechanisms[67,68]. These multi-dimensional struggles are shaped by exogenous developments (e.g. demographics, ideology, geo-politics, climate change, economic crises, wars, disasters). The MLP suggests that socio-technical transitions come about through alignments between processes at three levels: 1) niche-innovations build up internal momentum (through learning processes, price/performance improvements, support from powerful groups, increasing investments), 2) exogenous developments create pressure on the regime, 3) tensions in the regime create windows of opportunity for the expansion of niche-innovations[69,70]. Transitions in the MLP are not necessarily smooth curves, as in most IAM-analyses, but may involve setbacks and stop-start dynamics, e.g. when new governments reverse policies, when economic crises change priorities, or when niche-innovations have unforeseen consequences.

The MLP is a qualitative, appreciative framework that combines ideas from evolutionary economics (regimes, niches, routines, capabilities), sociology of innovation (innovation as a socially enacted process) and neo-institutional theory (actions are shaped by formal, cognitive and normative rules and institutions). MLP-studies typically assess the feasibility of low-carbon innovations and transition pathways by analysing niche, regime and external developments in the recent past, which allows a detailed identification of drivers and barriers in the present, which informs forward-looking interpretive assessments[71,72]. Some weaknesses of the socio-technical approach and MLP are the limited assessment of sustainability *outcomes* and achievement of future targets, reliance on qualitative case study methods, limited quantitative generalization, and focus on policy strategies rather than policy instruments[35].

Practice-based action research is useful because the approach reveal the messiness of on-the-ground initiatives in local practices. It represents a more engaged action-orientation to knowledge production with a more experimental approach[73,74]. The approach typically builds on partnerships between researchers and activists in grassroots innovations[37], community energy initiatives[75] or urban transitions-in-the-making[37]. The approach offers lessons for innovation and change that have relevance for wider transitions. First, it emphasizes the importance of broad coalitions of actors (e.g. project developers, local authorities, citizens, local shop owners, community groups)[76]. The co-creation of new objectives, practices and technologies are critical to new ways of doing things and to social acceptance. Second, approaching stakeholders as participants in innovation projects may tap into different kinds of motivations than the purely economic ones, for instance trust, cooperation, commitment, and collective action. Ostrom argued that polycentric systems, which explicitly acknowledge the importance of local experimentation and learning, are based on a different "behavioural theory of human action", which "recognizes the importance of context in affecting levels of trust and reciprocity"[77]. Third, local innovation projects should not be seen as the roll-out of a blueprint, but as an emergent learning-by-doing process[36]. Especially for highly-novel innovations, it is important to allow for tailoring of the innovation to specificities of local contexts as well as for creativity and learning that may lead to unforeseen solutions or novel functionalities[78]. Actors may change their beliefs and goals during the process via 'experiential learning', based on recursive interactions between action, experience, reflection and sense-making[79]. While practice-based action research offers detailed insights about actors' experiences, interpretations and problem-solving, it has some weaknesses such as: limited attention to wider structural contexts, short-term orientation (years instead of decades), limited generalization (because of emphasis on contingency, messiness and context specificity)[35]. Table 3 summarises the strengths and weaknesses of the three approaches.

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TABLE 3 ABOUT HERE.

Bridging and governance

The three approaches are characterized by fundamental differences in philosophies of science and ontological assumptions. They also highlight different dimensions of low-carbon transitions, focus on different scales (global to local), and address different temporalities: from future goals to the present in IAMs, from the recent past to the present and near-by future in the MLP, and focused on the present in practice-based action research.

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These differences imply that the approaches cannot be easily integrated. However, this does not necessarily mean that the only alternative is pluralism, in which incommensurable approaches are used separately. Instead, a third option is possible which makes crossovers and bridges between the different approaches to generate deeper and assessments of low-carbon transitions. Turnheim and colleagues[35] make a specific proposal for a structured dialogue between these three approaches, based on *alignment* (developing a shared problem formulation and framing), *bridging* (exchange of data and metrics, evaluations of low-carbon innovations, views on promising transition pathways) and *iterative interactions* (techno-economic checks of qualitative narratives and outcomes, socio-political feasibility checks of model outcomes, contextual constraints on local innovation projects). They suggest that such a bridging approach may enable "a more multi-dimensional evaluation of transitions as they unfold, informing governance decisions and practices". In our view, a potentially fruitful avenue for this 'pluralist bridging approach' is the following: IAMs first develop model runs of possible least-cost low-carbon mitigation pathways. Socio-technical analyses and practice-based action research then provide feedback on specific mitigation options, drawing on their specific strengths. Socio-technical analyses could provide information about actor strategies and struggles which influence the implementation of certain mitigation options; these could be hindering influences (e.g. resistance from big firms, limited political will in Parliament, public opinion concerned about non-climate issues such as austerity, jobs, or refugees) or stimulating influences (e.g. reorientation of big firms, successful new entrants, stronger ambitions from new government, greater sense of urgency in public discourse). Practice-based action research could analyse the number of local projects with certain mitigation options and the outcomes of learning processes (e.g. costs, co-benefits), which may be more (or less) positive than assumed in models. This feedback could then lead to revised IAMs and new model runs, in which certain mitigation pathways are downplayed and others favoured (based on different assumptions). While there is no guarantee that these iterative interactions will lead to an optimal consensus outcome, the process is likely to enhance awareness of potential risks and opportunities of mitigation pathways and of trade-offs between criteria such as cost-effectiveness, socio-political feasibility, and social acceptance.

Last, but not least, we aim to indicate how the three analytical approaches may be helpful for addressing different governance dimensions and knowledge needs of policymakers. Firstly, we suggest that the approaches may have greater relevance for different kinds of policymakers in polycentric governance systems[77]: IAMs at the global scale, practice-based action research at the local scale, and the MLP and sector-specific models at the national-sectoral scale. This suggestion heeds the warning by Petersen and colleagues: "While generic, untailored and untargeted climate knowledge has been effective for international policy dialogue, it is not fit for the purpose of supporting distributed climate action in the coming decades"[81].

Secondly, we suggest that the three analytical approaches of low-carbon transitions align with three academic perspectives on policymaking, which highlight different dimensions.

- IAMs align with *design and planning theories*, which see policy-making as a rational process of setting goals, making plans, implementing instruments, evaluating outcomes, and adjusting instruments[82]. In this policy theory, experts play important roles by providing information and measuring progress towards the goals. IAM may be used to offer goal-oriented analyses of the cost-efficiency of low-carbon options and their effectiveness (in decreasing greenhouse gas emissions and reaching climate goals).
- Socio-technical transitions theory aligns with *theories of policy networks* and *advocacy coalitions*, which conceptualise policy-making processes as involving negotiations, consultations and power struggles between policymakers and interest groups[83,84]. Socio-technical transitions theory may be useful to assess the socio-political feasibility and social acceptance and legitimacy of various low-carbon options, by analysing the interpretations, strategies and resources of different social groups.
- Practice-based action research aligns well with *theories of incrementalism* and *muddling through*, which see policy implementation as a local process of improvisation, tinkering, and learning-by-doing[85,86]. Particularly for radical innovations with high degrees of uncertainty and diversity (e.g. community energy initiatives, grassroots innovation, urban reconfiguration projects), it is difficult (and risky) to rapidly develop a clear-cut policy strategy. Instead, it is better for such a strategy to emerge from a succession of projects because this allows for flexibility, learning-by-doing and articulation of robust practices. Practice-based action research may inform such an emergent policy strategy by offering analyses of on-the-ground experiences, stakeholder concerns, and learning processes with low-carbon innovation initiatives.

We suggest that low-carbon transitions are best navigated through a combination of different analytical and policy approaches: 1) rational goal-oriented analysis with IAMs, culminating in a vision or general plan, 2) identification of feasible and legitimate pathways with socio-technical analysis, which are sufficiently supported by policy networks and advocacy coalitions, 3) assessments of real-world initiatives and projects to explore transition pathways and emerging options. This suggestion aligns with the synthesis of Mintzberg and colleagues who found that 'realized' strategies in complex situations arise from combinations between 'intended' (goal-rational), 'deliberate' (contextual) and 'emergent' (learning) strategies (Figure 1)[87]. This combination would enable a governance approach that accommodates both goal-oriented directionality and emergent experimentation and learning[88]. In sum, we conclude that the three analytical approaches offer different kinds of knowledge that together may underpin a multi-facetted transition approach in polycentric governance systems.

FIGURE 1 ABOUT HERE.

Text box 1: Examples of social (inter)actions that accelerate or slow down low-carbon innovation

* *Innovation races* may occur when firms change their perceptions and strategies from early resistance and closed industry fronts towards pro-active strategies. This pattern happened with hybrid-electric vehicles (HEVs)[89]. When Toyota marketed HEVs in America, other automakers were bemused because HEVs were more expensive and technically complicated. But when Toyota's sales of the Prius accelerated after 2004, they rapidly reoriented their strategy and also developed HEVs, propelled also by rising oil prices and fuel efficiency debates.

* *Political struggles* can accelerate low-carbon transitions, when politicians jockey for the 'green' vote and compete in proposing increasingly ambitious policy proposals. This happened in the UK in the mid-2000s when competition between Conservative and Labour politicians resulted in the ambitious 2008 Climate Change Act, which has underpinned low-carbon innovation since then[90]. But political struggles can also hinder low-carbon innovation, when policies are frequently changed (which creates investor uncertainty) or when low-carbon policies are scrapped, as happened with the Australian carbon tax in 2014 and a raft of UK low-carbon policies in 2015, when a newly elected Conservative government prioritized cost-savings over long-term climate innovation.

* *Social acceptance* may accelerate diffusion, as happened with rooftop solar-PV and electric bicycles which both benefited from unforeseen enthusiasm. But social acceptance may also create unforeseen problems for low-carbon options because of public concerns about safety risks or pollution (as is currently happening in some countries with regard to onshore wind, CCS, and shale gas) or because of unintended consequences (e.g. biofuels in relation to food prices and deforestation). Social acceptance problems may also arise from a lack of consultation and technocratic implementation processes that give limited consideration to concerns of local residents, as happened with onshore wind in the UK[91]. Perceived unfairness and distributional consequences may also hinder social acceptance. Large-scale solar-PV installation, for instance, led to concerns in the UK about 'fat cats' enjoying wind-fall profits[92].

* *Social and user innovation* is often difficult to foresee. The last ten years have seen a strong entry of citizens, NGOs and local communities into electricity production ('community energy'), which in countries like Germany is threatening the business models of the Big Four utilities. Innovations like rooftop solar-PV are also having

knock-on effects in the sense of enhancing energy awareness of households, which then leads to subsequent innovations (e.g. insulation, energy-efficient appliances).

Table 1: Different philosophies of science (substantially expanded from[59,93-95])

	Positivism	**Post-positivism, critical realism**	**Constructivism**	**Relativism, postmodernism**
Assumptions about nature of reality	Reality is independent and objective (i.e. empirical, measurable).	Reality is independent and layered, consisting of surface level 'events', mediating mechanisms, and generative structures.	Reality is socially constructed through intersubjective meanings.	There is no single reality, but multiple stories and narratives of different realities.
Explanatory goal and style	Deterministic: uncover general laws and relations between variables (and represent these mathematically).	Interpretive: Explain processes by analyzing actions in the context of structures, mediated by causal mechanisms.	Interpretive: describe evolving meanings to understand reality construction.	Critique dominant narratives; uncover hidden interests and power structures; emancipate the silenced voices; raise normative questions (on justice, equity, fairness).
Methodology	Experiments, model simulations, manipulation of variables and quantitative data.	Trace processes and event chains (quantitative or qualitative); attempt to infer causal	'Follow the actors' in real-life contexts; describe interpretations, disagreements and (emerging) consensus.	Reveal contradictions and paradoxes; show multiplicity and alternatives; opening up debates.

		mechanisms and deeper structures.		
Typical disciplines	Mainstream economics, system analysis, operations sciences.	Structuration theory; neo-institutional theory.	Interpretive (micro)sociology, phenomenology, social psychology.	Critical theory, post-structural sociology, critical management studies, critical discourse theory, cultural studies.
View on governance	Policymakers 'outside' the system, pulling 'levers' to steer developments.	Policymakers are part of the system and dependent on other actors. They can try to 'modulate' ongoing dynamics, but not steer at will.	Deliberative governance, based on consultation and participatory debate. Governance as open-ended learning process, based on experiments, projects and sense-making.	Policymakers align with societal elites to protect vested interests.

Table 2: Foundational assumptions in different ontologies (adapted from[96])

	Causal agent	**Causal mechanism**	**Highlighted dimensions of low-carbon transitions**
Rational choice	Individual, self-interested actors.	Decentralized choice by instrumental rationality.	Relative cost of low-carbon options; market competition; investments and purchase decisions; financial incentives (taxes, subsidies, cap-and-trade).
Interpretivism	Individual actors with varying ideas and interpretations.	Social interaction, construction of shared meaning, sense-making, learning, debates.	Differing meanings and narratives of low-carbon options (e.g. wind turbines as renewable energy, bird shredders, horizon pollution, noise creators); societal debates, controversies, social acceptance of nuclear power, CCS, fracking, coal.
Structuralism	Shared and taken-for-granted cultural deep structures.	Deep structures operate 'behind the backs' of actors, shaping their beliefs and preferences.	Taken-for-granted cultural beliefs, discourses and frames, e.g. is climate change a 'market failure' or 'planetary boundary'? Are low-carbon technologies sufficient or are deeper changes needed in behaviour or economic structures?
Conflict theories	Collective actors (groups, classes) with different interests and resources.	Conflict and power struggle over material resources and positions.	Resistance to change from carbon-based and energy intensive industries (e.g. oil, coal, iron, steel, cement, petro-chemicals, fertilizer). Calls for action (and subsidy) by renewable industries (wind, solar, bio-based); economic and socio-political

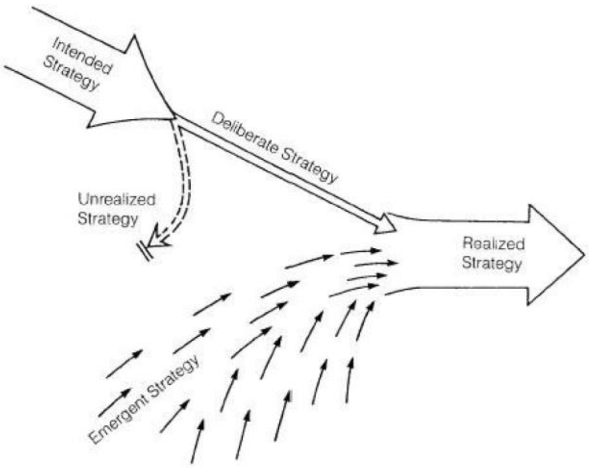
			struggles, including marginalization of certain actors and voices.

Table 3: Overview of strengths and weaknesses of the three approaches[35]

Approach	***Strengths***	***Weaknesses***
Quantitative systems modelling	- Robust and highly formalized research methods - Consistent analysis of complex systems - Attention to system interactions (e.g. sectors) - Attention to problem interactions - Synthetic analysis of multiple options - Links policy goals to required physical changes - Ability to calculate effects of policy options on transition pathways - Simple and coherent policy advice	- Oversimplification of social realities, little attention to actors and behaviours (politics, power struggles, beliefs, strategies) - Limited scope for changing economic, social and institutional rule-sets - Over-reliance on economic mechanisms - Limited attention to implementation process

Socio-technical analysis	- Fine-grained analysis and understanding - Attention to different levels and temporalities - Attention to relevant socio-technical dimensions - Attention to multiple actors and behaviour types - Analysis of institutions and changing 'rules of the game' (including shared cognitions and norms) - Attention to inertia of existing systems - Policy advice sheds light on uncertainties	- Mainly descriptive (qualitative case studies) - Qualified generalization (context-specific, pattern-based, multiple and changing causal mechanisms) - Limited forward orientation to political targets - Policy advice focuses on general strategies (patterns) rather than instrumentality
Initiative-based learning	- Analyses and /or engages in real-world initiatives as experimenters - Attention to local level and implementation - Attention to actor-relevant dimensions (behaviour, legitimacy, learning, inclusion, etc.) - Relevance to stakeholders and practitioners - Policy advice is rooted in practice	- Limited methodological standardisation - Often context-specific and short-term oriented - Limited attention to wider structural contexts - Difficulty to generalize lessons for entire transitions

Figure 1: Realized strategies arising from combinations between intended, deliberate and emergent strategies[87]



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